EVALUATION OF WELDING CONSUMABLES AND PROCEDURES FOR SUBMARINE CONSTRUCTION

AR-008-624

AD-A279 266

B.F. DIXON

MRL-TR-94-3

FEBRUARY 1994

MATERIALS RESEARCH LABORATORY

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Evaluation of Welding Consumables and Procedures for Submarine Construction

Brian Dixon

MRL Technical Report
MRL-TR-94-3

Abstract

This report provides a summary of three developments in the welding of BIS 812 EMA and HY 590 high strength steels for the new RAN Collins Class submarine. Firstly, the established benchmark properties for Charpy energy, dynamic tear energy and elongation in the tensile test have been reviewed in the light of data collection from US, Australian and Swedish sources. A new set of benchmarks is proposed which takes into account the interrelationship between notch toughness, elongation and explosion bulge performance. Secondly, the influence of welding procedures (notably heat input) on weld toughness is discussed and heat input and preheat ranges are recommended which ensure that unrealistic welding parameters are not used simply in order to pass the explosion bulge test. Thirdly, a detailed microstructure and hardness survey on a weldment which marginally satisfied the requirements of explosion bulge testing is described. The results suggest that welding electrodes and procedures which were designed for the more traditional quenched and tempered steels such as HY 100 can also be used on the new BIS 812 EMA steels.

DEPARTMENT OF DEFENCE
DSTO MATERIALS RESEARCH LABORATORY

Published by

DSTO Materials Research Laboratory
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Telephone: (03) 246 8111
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AR No. 008-624

APPROVED FOR PUBLIC RELEASE

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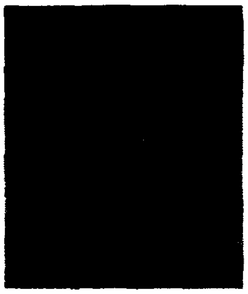

Brian Dixon, currently a Principal Research Scientist in Ship Structures and Materials Division MRL, received his degree of Bachelor of Applied Science from the Royal Melbourne Institute of Technology in 1981, Master of Applied Science from the University of Melbourne in 1984 and Doctor of Philosophy from the University of Melbourne in 1988.. He has been employed at MRL since 1978, undertaking experimental development and fundamental studies into weld solidification cracking in a wide range of steels and stainless steels. He has also worked on techniques for the improvement of weld zone properties for high strength steels.

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Evaluation of Welding Consumables and Procedures for Submarine Construction

1. *Introduction*

The main requirements of weldments in modern submarine hulls are that they have adequate strength and fatigue resistance to withstand the stresses associated with deep diving, and adequate toughness to survive shock loading which might be caused by exploding mines or torpedoes. The first objective is easily obtained. A wide range of welding consumables is available which can produce weld deposits having yield strengths in the range 550-900 MPa, the strength range of modern submarine steels, and modern weld designs incorporating dressed weld toes can produce a threefold increase in fatigue resistance [1].

The second objective of providing adequate toughness is much more difficult to achieve and considerable effort has been devoted to this goal by universities, consumable suppliers and research organisations around the world. The main difficulty with weld deposits is that, by comparison with steel making technology, the scope for thermal and mechanical treatment of the final weld zone is limited. Therefore the main emphasis has been on control of weld metal composition, weld parameters and weld thermal cycling to produce inherently tough acicular ferrite microstructures which have small grain size and high angle grain boundaries [2]. Such techniques can be used for welding of the Collins submarines where it is necessary to require yield stresses greater than 690 MPa. For higher yield stress steels (750-900 MPa) it has been difficult to obtain adequate weld metal strength from acicular ferrite microstructures and less tough, martensitic deposits have generally been used [3].

There is also considerable interest in the properties of weld heat affected zones because these regions have the composition of the parent metal but are subjected, to varying extents, to the thermal cycles associated with welding. The consequence of this is that heat affected zones often have greater strength and hardness than the adjoining weld and parent metals but may have significantly reduced toughness. Therefore welded panels which have excellent weld metal and parent metal properties often fail along one side of the heat affected zone when they are subjected to explosive loading. In the case of some micro alloyed steels the heat affected zones have lower hardness than both the weld and parent metal and, in these cases, failure then occurs through the heat affected zone.

For some time this problem of inherent weld heat affected zone sensitivity was exacerbated by the US Navy practice of requiring weld deposits to have overmatching strength compared with the parent metal. The justification of this requirement was a perceived need to compensate for lower fracture toughness of the weld and the more likely occurrence of defects in welds. The notion was that higher strength welds would deflect strains onto adjacent zones and thereby avoid critical strains in the weld metal. In fact, the practice tended to make matters worse because it led to increased plastic strain being imposed upon inherently sensitive regions on both sides of the heat affected zones during overall deformation of a welded panel, and hence an increased risk of premature failure. As a consequence of work undertaken at MRL [4,5] and other establishments in UK and US, this practice is under review.

The purpose of this report is to present investigations into three aspects of welding technology for high strength steels used in naval construction.

The first part is a review of data collected from US, Australian and Swedish sources about the performance of various weld deposits when subjected to a range of mechanical tests, including the explosion bulge test. The background to this work was described in a conference paper [6] where it was argued that appropriate benchmark properties for Charpy and dynamic tear energy, and elongation in the tensile test can give a realistic indication of performance in the explosion bulge test[1]. The purpose of the work was to review these benchmark properties in the light of recent test results.

In the second part, an assessment was made of the significance of welding parameters, notably heat input, in obtaining adequate weld toughness for submarine applications. By using highly contrived welding procedures, especially low heat input passes, it may be possible to produce tough weld deposits which are capable of easily passing the explosion bulge test using a wide range of commercial welding electrodes. However, because such procedures are impractical for submarine fabrication, can lead to cracking problems, and are unlikely to be adhered to, a restricted range of welding procedures is proposed for fabrication of explosion bulge test panels. These procedures are considered to be comparable to those which might realistically be used for fabrication of the submarines.

The third part of this work involved a detailed microstructure and hardness survey of weld deposits, heat-affected-zones and parent metals in welded OX 812 EM[2] steel plate which marginally satisfied the explosion bulge test requirements. This steel is the prototype of BIS 812 EMA steel manufactured in Australia and used in the construction of the RAN Collins class submarine. This particular sample is of considerable importance since it provides a good indication of the minimum acceptable standard of welding technology for submarine construction.

[1] A brief description of the explosion bulge test is provided in Appendix 1

[2] A microalloy augmented martensitic quenched and tempered steel. Composition (wt %): 0.12 C, 0.84 Mn, 0.3 Si, 0.002 S, 0.01 P, 1.22 Ni, 0.51 Cr, 0.4 Mo, 0.03 V, 0.2 Cu, 0.06 Al, 0.003 B, 0.01 Nb, 0.007 N, 0.003 O. Properties: 743 MPa yield, 801 MPa, UTS, 122 J Charpy energy at -85°C.

2. *Review of Data on Performance of Weld Deposits*

In this first part, the mechanical and explosion bulge test results for a range of welds are analysed to determine the validity of current benchmark values from small scale mechanical tests (Charpy, dynamic tear, tensile elongation etc) for predicting explosion bulge performance [6], and to identify any interrelationships between results of the various test procedures. The data used for this analysis were taken from references 7, 8 and 9 combined with recent results from the testing, in Australia, of OX 812 EM steel plate.

Specifically, the three different test methods were tested for correlation against each other for efficacy in predicting explosion bulge test outcome.

Results are presented in Figs 1, 2 and 3. The benchmark levels given in these figures are taken from reference 4. Figure 1 superimposes the explosion bulge test results on plots of Charpy impact energy at -18°C against dynamic tear energy at -1°C; two test temperatures for which benchmark properties have been derived. The error bars in Fig. 1 represent the range of results obtained and the explosion bulge performance is described according to the criteria used in reference 4 or the relevant test report. In general, 'pass plus' refers to test plates that bulged evenly to produce thinning of 18% or greater with minimal cracking; 'pass' refers to plates which clearly met the specification; 'marginal' refers to plates which had extensive cracking but obtained 12-16% thinning[3]; and 'fail' refers to plates that showed extensive brittle fracture at low values of thinning.

Figure 1 shows that Charpy and dynamic tear energy, at the test temperature used, have an approximately linear relationship, with dynamic tear energy at -1°C being about eight to ten times greater than Charpy energy at -18°C. Both benchmark values appear to give a useful indication of explosion bulge performance, however the weld in one steel which failed the explosion bulge test actually exceeded the dynamic tear benchmark value.

The results for explosion bulge testing superimposed on dynamic tear energy at -29°C against Charpy energy at -51°C are presented in Fig. 2, using the same conventions as those in Fig. 1. Again it can be seen that the relationship between Charpy and dynamic tear energy is approximately linear, however the spread of results is greater than in Fig. 1. The Charpy benchmark value in this case seems to be valid with all marginal and fail results being below this benchmark and all pass results above it. The dynamic tear benchmark at -29°C has not been as successful because two marginal test plates passed this benchmark and one successful plate failed it. The three plates which clearly failed explosion bulge testing also failed to meet both the Charpy and the dynamic tear benchmark.

Since the graphs show that Charpy energy has an approximately linear relationship with dynamic tear energy at the temperatures described, plots of elongation against dynamic tear energy were not proceeded with, and only that property giving the most reliable benchmark, Charpy energy at -51°C, was chosen for subsequent work.

[3] Some of these test plates were declared a pass and others were failed.

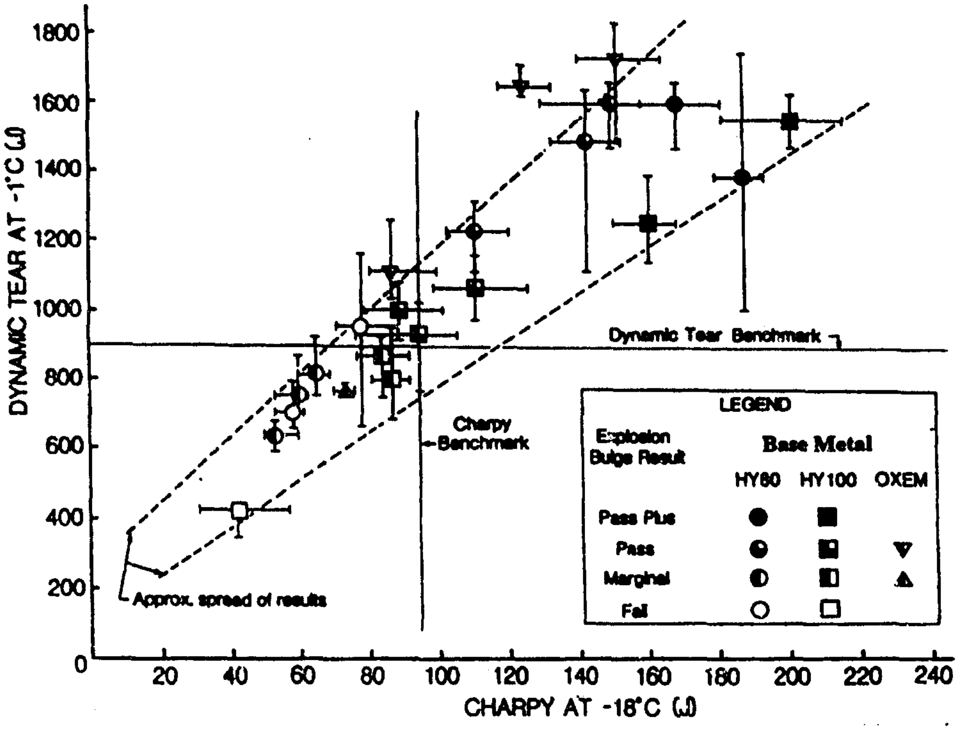

Figure 1: Explosion bulge performance against dynamic tear energy for weld metals at -1°C and Charpy energy at -18°C. Descriptions of the four classifications of explosion bulge test results are provided in the text. Electrodes used for HY 100 and OXEM are identical.

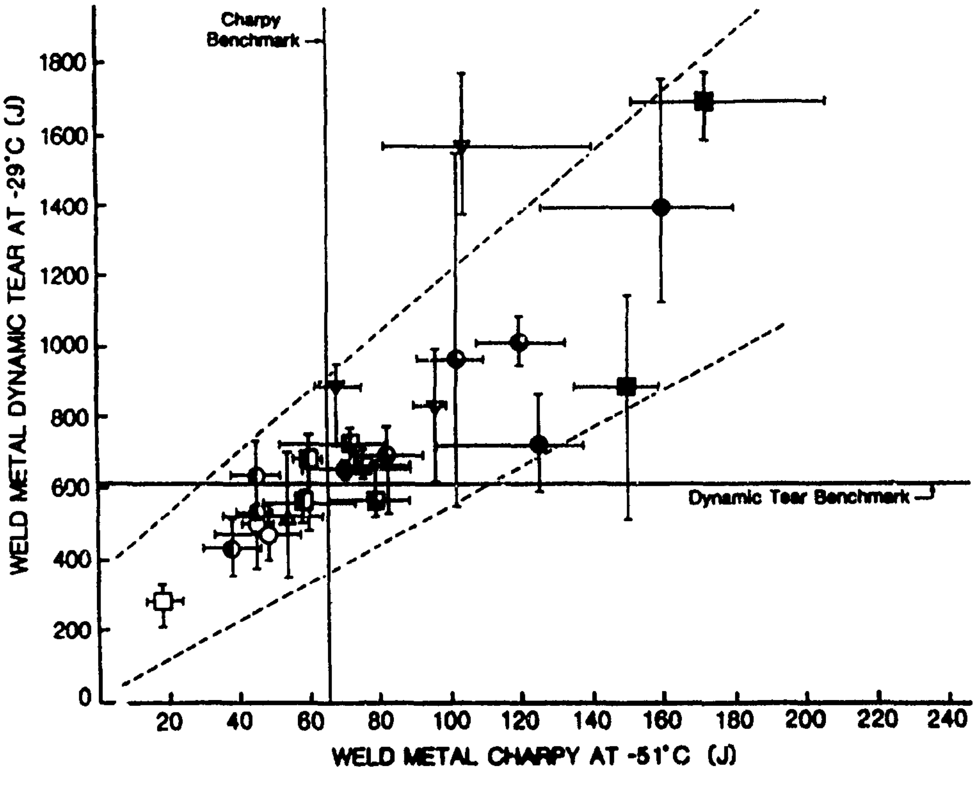

Figure 2: Explosion bulge performance against dynamic tear energy at -29°C and Charpy energy at -51°C.

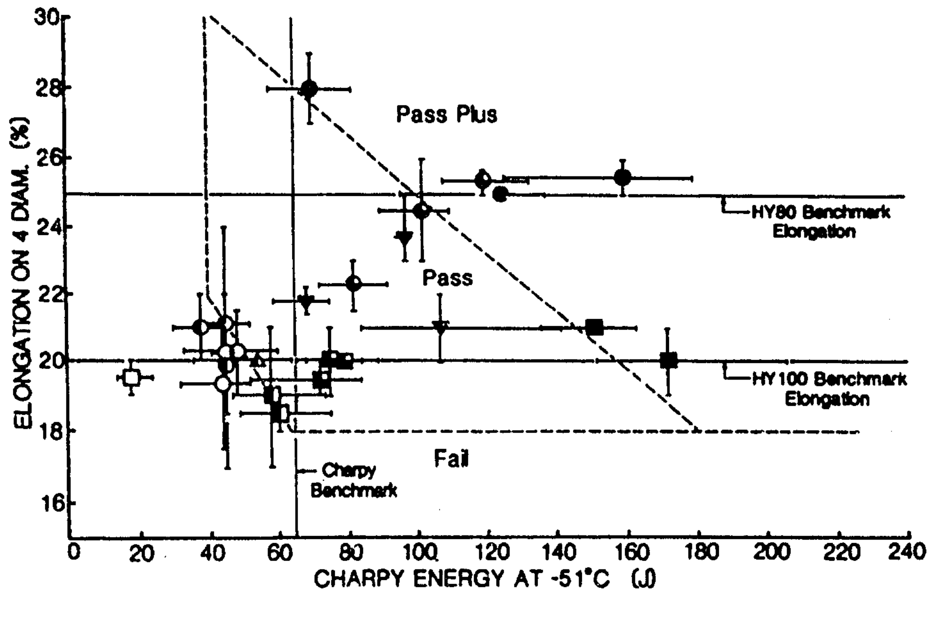

Figure 3: Explosion bulge performance of weld metals against their Charpy energy at -51°C and elongation.

Results presented in Fig. 3 show that there is an interrelationship between elongation, Charpy energy at -51°C and explosion bulge performance. Test plates which clearly failed the explosion bulge test had low values of both Charpy energy and elongation. The marginal results were all clustered in a region about the diagonal shown as a dashed line extending from 40J, 22% elongation to 60J, 18% elongation and pass results were all clearly to the right of this line.

The importance of measuring both elongation and Charpy energy to give an indication of explosion bulge performance is demonstrated by the 'pass plus' results in Fig. 3. For example, on one hand, a welded HY-80 steel which just passed the Charpy benchmark value but whose elongation was high (28%) performed well in the explosion bulge test. On the other hand, a welded HY-100 steel which had elongation properties down to benchmark level, but high Charpy energy also gave good explosion bulge performance.

The work has vindicated the particular choice of benchmark values [2] for Charpy energy and, to a large extent, for HY-100 elongation. However, these results show that the HY-80 benchmark elongation is obviously too stringent, because a number of welds performed very well in the explosion bulge test despite having elongation values considerably lower than this benchmark.

It is noted however (Fig. 3), that electrodes intended for welding HY 80 normally gave higher values of elongation than those intended for HY 100 because of the different strength levels. It may therefore be appropriate to choose a higher benchmark elongation for the HY 80 electrodes in order to discriminate between the various electrode formulations.

The problem with the use of existing benchmark properties for Charpy energy, dynamic tear energy and elongation is that they fail to take into account the

interrelationships between these values that have been identified here. For example, a welded test plate which has a high Charpy energy value may be excluded from explosion bulge testing, which it might in fact easily pass, simply because it has not met a specified elongation value. To overcome this problem the three zones (pass plus, pass and fail) presented in Fig. 3 are offered as an improved indication of the eventual explosion bulge performance.

3. *Welding Procedures*

3.1 Heat Input

In order to obtain the specified strength level for a particular electrode type, the electrode manufacturer controls the alloy content of the flux coating and requests that the fabricator use a specified range of welding currents. If a fabricator uses higher welding currents than those specified, and other welding parameters, eg. voltage and travel speed, are held the same, then the cooling rate of the weld is reduced and the weld deposit generally has a large grain size with reduced strength and possibly toughness. Moreover, the higher arc current causes greater loss of strength-conferring elements such as Mn and Si. This further contributes to the lower strength of the deposit. Conversely, if a fabricator uses lower welding currents, both the strength and toughness of the weld deposit can be increased.

In practical fabrication, manufacturers generally seek to use high welding current in order to increase productivity in terms of kg/h of weld metal deposited while customers and operators of submarines seek optimum strength and toughness, which may be consequent upon cooling rates only attainable at low welding currents. This means that the electrode manufacturer is obliged to target his product at a compromise current range which enables the agreed minimum tensile strength and toughness to be obtained at commercially attractive rates of weld deposition.

In earlier work by the author [5] an MMA welding procedure was devised which produced exceptionally good performance in the explosion bulge test, partly because a narrow range of heat input value centred upon 1.8 kJ/mm was used. The desired weld metal tensile strength was obtained in that case by using a welding electrode that was intended for lower strength applications. A similar technique was used for the mechanical test results presented in Figs. 1-3 for the OX 812 EM steel. For the three tests identified by inverted triangle plotting symbols, heat input values as low as 1.2 kJ/mm were used and the nominal strength level of the welding electrode was considerably lower than the actual strength of the weld deposit [6][4].

[4]This work was undertaken using an early formulation of Swedish electrodes at a time when it was thought to be difficult to obtain a combination of high strength and toughness without resorting to low heat input welding techniques. The test results were not accepted as valid qualification of the electrodes for use on the Collins class of submarines.

Since it is generally uneconomical to weld submarines or surface vessels by MMA using heat input values consistently as low as 1.2 kJ/mm, any apparently successful mechanical test results which might be obtained by using these values should not be considered as valid qualification for submarine use. However, with conventional electrodes it may well prove impossible to obtain weld deposits which satisfy the requirements for explosion bulge testing when higher heat input values, say 2.2 kJ/mm and above, are used because of insufficient toughness. Therefore a compromise range of heat input values is urgently required so that manufacturers can design electrodes, testing authorities can standardise welding procedures and fabricators can design weld joints with some assurance that the performance of the welded fabrication is similar to that obtained in explosion bulge testing.

In summary, it is well established that heat input can have a dramatic effect on weldment toughness with lower heat input welds generally giving greater toughness and hence increased likelihood of passing the explosion bulge test. For nominally 690 MPa yield stress weld metal there may be a significant degradation in toughness at heat inputs greater than 2.2 kJ/mm [8]. Values of heat input below 1.6 kJ/mm are rarely used for commercial fabrication with the MMA technique. If the explosion bulge test is being used to compare the performance of welding consumables, it is therefore essential that a similar range of realistic welding procedures are used on each panel.

It is recommended that the minimum heat input value for MMA electrodes when welding BIS 812 EMA steel be 1.6 kJ/mm and that the maximum be any value up to 2.2 kJ/mm which can be shown to perform satisfactorily in the explosion bulge test. The target value of heat input should be about 2.1 kJ/mm.

3. 2 *Combined Effects of Heat Input and Preheat*

As with heat input, control of weld metal toughness can also be achieved by varying the level of preheat applied to a joint. Figure 4 is a modified version of a schematic diagram published by AWRA [10] which shows the 'window' of preheat and heat input values which can be used for quenched and tempered steels such as HY 80 and BIS 812 EMA. The 'window' has three boundaries which can be defined as follows (see Fig. 4):

1. Excessive preheat can result in over tempering of the heat-effected-zone which usually causes a reduction in strength, hardness and toughness.

2. Excessive heat input may also cause strength loss, softening and a reduction in weldment toughness.

3. Insufficient preheat and heat input may lead to excessive HAZ hardness and a risk of hydrogen cracking.

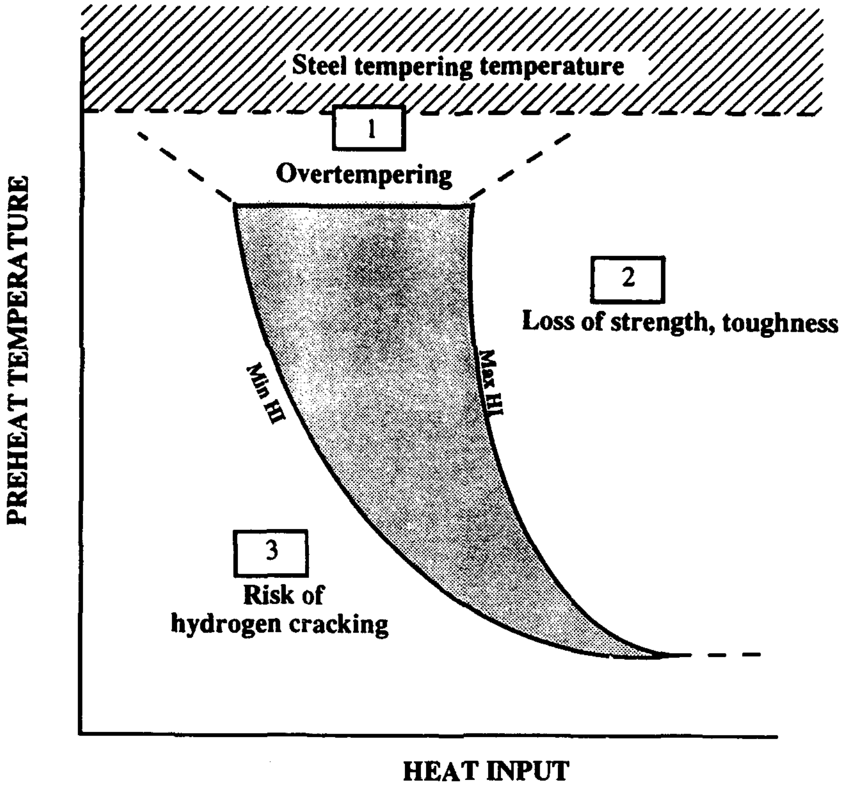

Figure 4: 'Window' of acceptable preheat and heat input values for the welding of quenched and tempered steels. The three regions marked 1, 2 and 3 are described in the text.

Two important points arise from this diagram:

(a) If welding heat input is reduced to improve the toughness of weld deposits then the preheat temperature must be increased.

(b) Up to the maximum preheat temperature which can be used, the range of acceptable heat input values steadily increases. This means that larger errors in the welding heat input can be tolerated if the preheat temperature is higher.

As discussed in reference 5, the optimum combination of strength, ductility and toughness of a complete weldment can be obtained by using the maximum preheat value (without running the risk of over tempering) in combination with the minimum heat input (the top left hand corner of Fig, 4). This provides small weld beads having fine grain size, maximum volume fraction of equiaxed grains, and optimum tempering of the heat affected zones associated with preceding

weld runs. This regime also minimises the risk of HAZ cold cracking because high preheat values encourage the diffusion of hydrogen. Unfortunately, these preheat values are also the most expensive to produce. Furthermore, it is not practicable to approach this corner too closely because the scope for tolerable variation in welding procedures diminishes. In other words, the closer that welding conditions approach the window boundary, the greater is the risk of accidentally trespassing outside it.

It is therefore recommended that preheat and heat input values be selected which are closer to the centre of the 'window' in Fig. 4. To do this, it is essential to determine scales for Fig. 4 which are applicable to BIS 812 EMA steels used in the Collins submarines. This work is currently being undertaken and some discussion about welding procedures that are close to the top left hand corner of the window in Fig. 4 is included in the following section.

4. *Metallurgical Assessment of Welds in OX 812 EM Steel*

As reported previously [11] the welded OX 812 EM prototype of the BIS 812 EMA steel used in construction of the Type 417 Submarine has marginally passed the mechanical test requirements, including explosion bulge testing, stipulated by MRL. Heat input values for these plates were in the range of 1.2-1.8 kJ/mm and preheat and interpass temperatures were 150°C. The welding technology used for these test plates is of importance because, as described above, this standard represents the minimum necessary to pass explosion bulge testing with steels of this type. It is therefore particularly useful to examine the metallurgy of these welds.

A cross-section taken from one of the welds in an explosion bulge test panel of Swedish origin is provided in Fig. 5. It is noted that the MRL 'Top Hat' procedure [5] has been adopted in the welding of this plate. This macrograph also shows the approximate location of specific areas subjected to detailed metallographic investigation (Appendix 2). These areas, designated A to N in Figs. 5 and Appendix 2, were chosen to represent a range of compositions and thermal histories as summarised in Table 1. Average hardness values for each area are also given in Table 1.

As shown in Table 1 the various areas can be divided into three groups depending upon their location.

First, the parent metal was largely composed of martensite, however bainite, ferrite and grain boundary pearlite (or perhaps M^*[12]) occasionally appeared as the consequence of particular thermal cycles. The grain boundary features at region H may be fine cementite-ferrite aggregates associated with inter critically reheated, course grained HAZ as discussed in reference 12. The hardest region of the HAZ (area A) was the area which benefited least from tempering by subsequent weld cycles. This Area A is small and immediately over ductile parent metal which can resist development of any cracking in the region [5].

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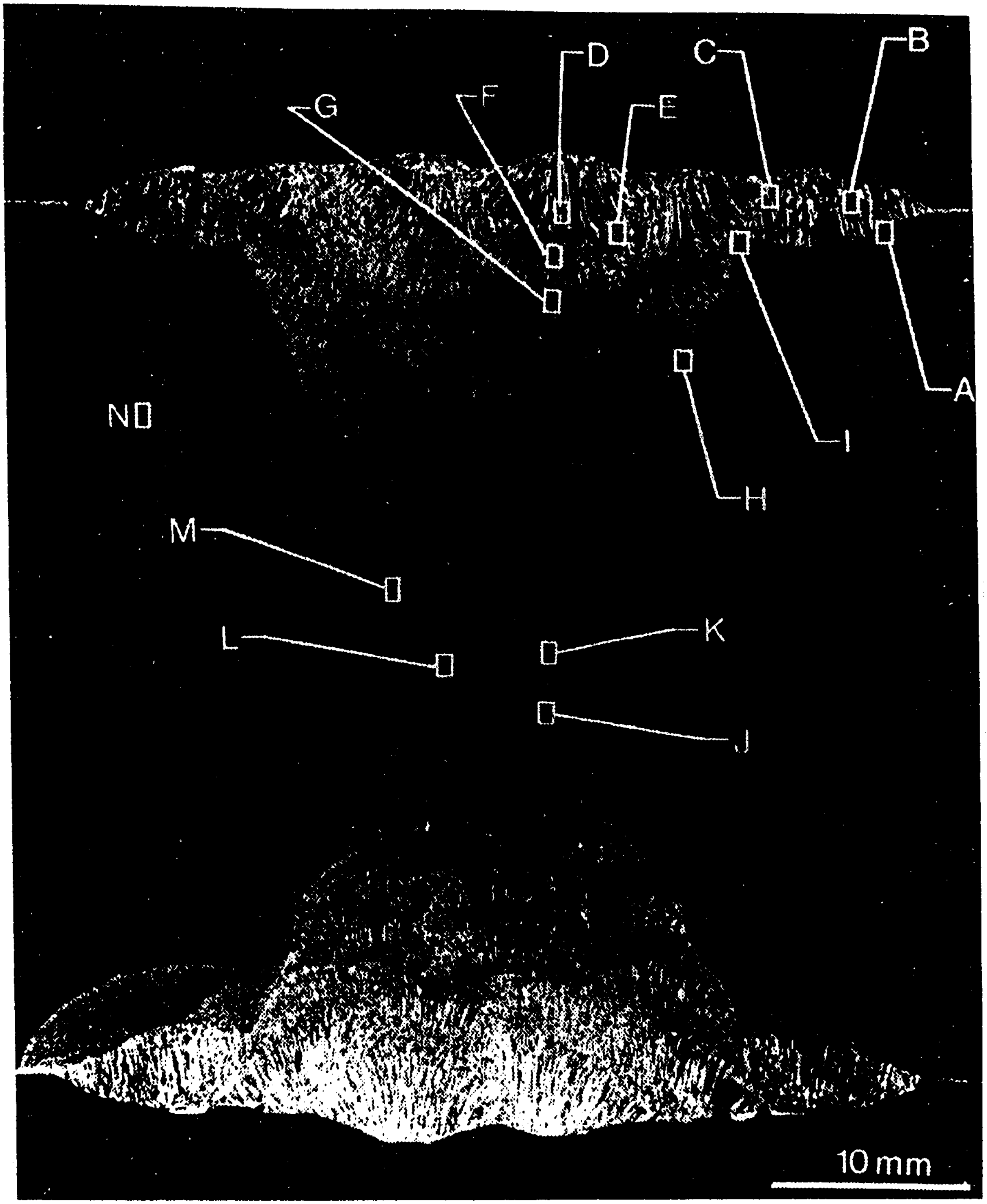

Figure 5: Section of a weld in [illegible] steel which marginally passed the explosion bulge [illegible] are given in Appendix 2. Note [illegible] the MRI [illegible]

Table 1: Description of Weldment Zones in Figure 5

Location	Post Weld Thermal Cycles	Code	Microstructure	Hardness (HV_{30})
Parent Metal	0	N	Tempered martensite	260
" HAZ	1	A	Martensite +15% bainite	329
"	2	H	Martensite + ferrite + GB pearlite	268
"	2	M	Martensite + bainite	305
"	3	I *	Tempered martensite	315
"	2	K	Martensite + 20% bainite	304
Weld Metal, High Dilution	0	B	Fine acicular ferrite	277
"	1	C	Acicular ferrite	282
"	2	J	Acicular ferrite	288
" *	2	L	Coarse acicular ferrite	293
Weld Metal, Low Dilution	0	D	Coarse acicular ferrite + 10% pro-eutectoid ferrite	312
"	1	F	Med acicular ferrite	300
"	2	E	Med acicular ferrite	229
"	3	G	Fine acicular ferrite + GB ferrite	279

* Located in plate centre

Second, the high dilution region of the weld was composed entirely of acicular ferrite and had a narrow range of hardness values (277-293 HV_{30}). These microstructure and hardness properties are near optimum for shock resistance. A small region of high dilution weld metal in the plate centre (Region L) had coarser acicular ferrite in the weld microstructure and the highest hardness (293 HV_{30}) of the high dilution weld beads.

Third, the low dilution weld metal had coarser acicular ferrite microstructures and some pro-eutectoid ferrite. Hardness varied from 229 to 312 HV_{30}, with the hardest weld deposit occurring in the final (untempered) weld pass and the lowest hardness occurring in weld metal which had experienced two thermal cycles after welding. This suggests that a wide variation in properties may be expected from low dilution weld deposits.

These weld metal microstructures and hardness values fall within ranges which are widely held to be consistent with satisfactory toughness and shock resistance [2]. They therefore suggest that no obvious problem exists, in this regard, with the welding consumables and procedures that were used. This is reassuring because the welding electrodes used in this work are primarily designed for steels such as HY-80 which contain higher percentages of the alloying elements such as nickel. It is also reassuring to know that welding procedures which were designed by MRL for use on HY-80 steels can be transferred to the new BIS 812 EMA steels with equal apparent success.

The problem with the particular weld examined is that low heat input values (1.2-1.8 kJ/mm) and high preheat values (150°C) were used to produce a weld deposit that marginally passed the explosion bulge test; that is, the welding parameters which were chosen lie in the top left hand corner of Fig. 4. This suggests that when using the particular electrode formulations, the only acceptable welding procedures occur at the low productivity, tightly defined, top left hand corner of Fig. 4. Further work has been undertaken by the author [13] to

measure the effect on weld and HAZ toughness of using reduced preheat and increased heat input with more recent formulations of tough, high strength electrodes. The goal of the work is to develop welding procedures that are both practical and offer increased tolerance to welder variability.

4. *Summary*

1. A diagram has been devised which accurately predicts the explosion bulge performance of weld deposits in high strength steels based upon Charpy energy at -51°C and elongation in the tensile test. This diagram is considered to be an improvement upon the individual benchmark values used up until now because it makes allowance for the interrelationship between toughness (as measured by Charpy V-notch) and ductility (as measured by tensile elongation) in predicting explosion bulge performance.

2. To ensure consistency between the results of explosion bulge testing and the performance of welds used for high strength steels on the Collins class submarines, the welding procedures for both should be similar. It is therefore recommended that welding heat input values for explosion bulge test panels and subsequent submarine construction be restricted to a minimum value of 1.6 kJ/mm and a maximum value no greater than 2.2 kJ/mm.

3. In submarine fabrication, heat inputs in excess of 2.2 kJ mm^{-1} should only be permitted in cases where an explosion bulge program has passed for welds laid at the particular value of heat input.

4. Welding procedures which were developed by MRL for use with HY-80 and HY-100 steels can perform adequately when used for the OX 812 EM steels.

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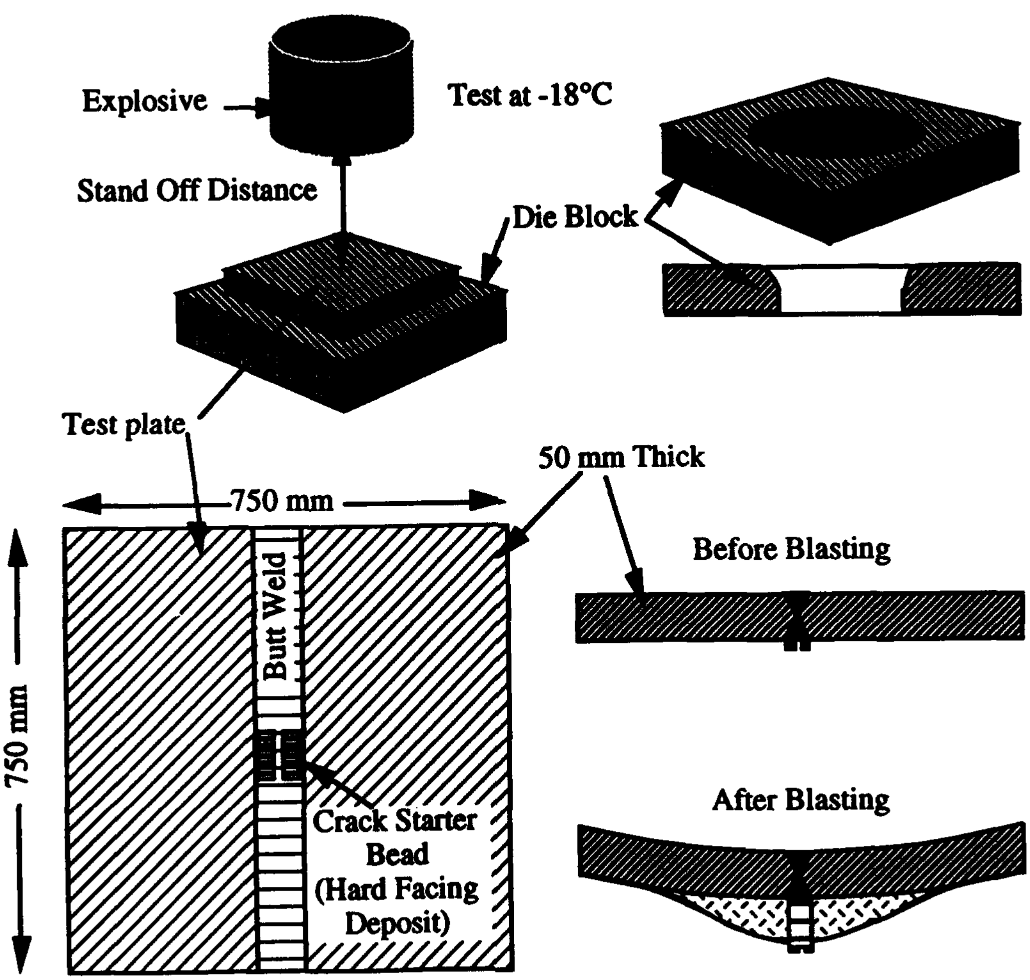
Appendix 1

Brief Description of the Explosion Bulge Test

Since the submarine hull may have to withstand very high strain rates such as that which might be caused by an explosion, a very stringent test program has been devised for the qualification of steels and welding consumables. This program includes standard test procedures such as the Charpy and tensile tests It also includes the ultimate toughness test for submarine hull construction; the *explosion bulge test* (EBT).

In the EBT, test panels of hull steel, usually containing a weld, are cooled to temperatures well below minus 18°C and then placed on a die block as shown below. An explosive charge is placed a fixed distance above the centre of the plate and this charge is detonated when the plate has warmed up to exactly minus 18°C. The force of the explosion dishes the centre of the test plate into the hole in the centre of the die block.

Explosion Bulge Test



Test Plate Design

A test plate is considered to pass the EBT *if it* obtains a reduction in thickness of 14% at the plate centre without extensive cracking.

The *crack starter test* is a variation of the bulge test in which a sharp crack is introduced at the centre of the test plate. To obtain the crack, a brittle hard facing deposit is welded onto the surface of the test plate at the plate centre and this weld is subsequently notched by grinding. A single explosive blast at the test temperature then induces a crack into the test plate. A further blast is then provided at -18°C and, if this does not cause the crack to propagate beyond the central region, the test has passed.

The explosion tests are undertaken on two to six test plates as required.

Details of the Explosion Bulge Test procedure are contained in the United States Military Standard, MIL-STD-2143 (SH), Dated November 1983.

Appendix 2

Photomicrographs of the Weld Zone Regions Identified in Figure 5

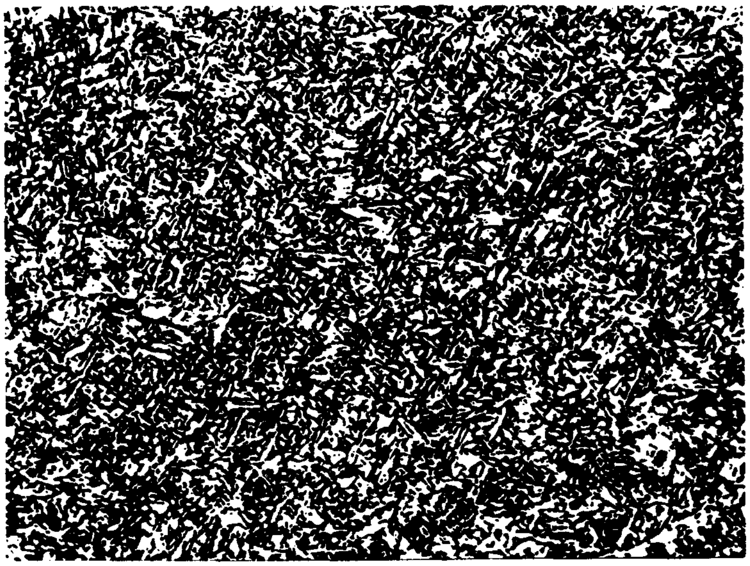
A

x100

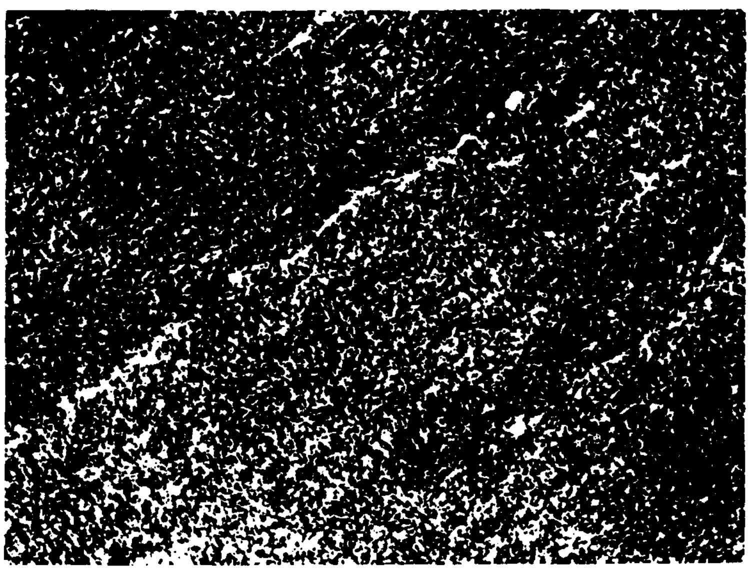
x500

B

x1000

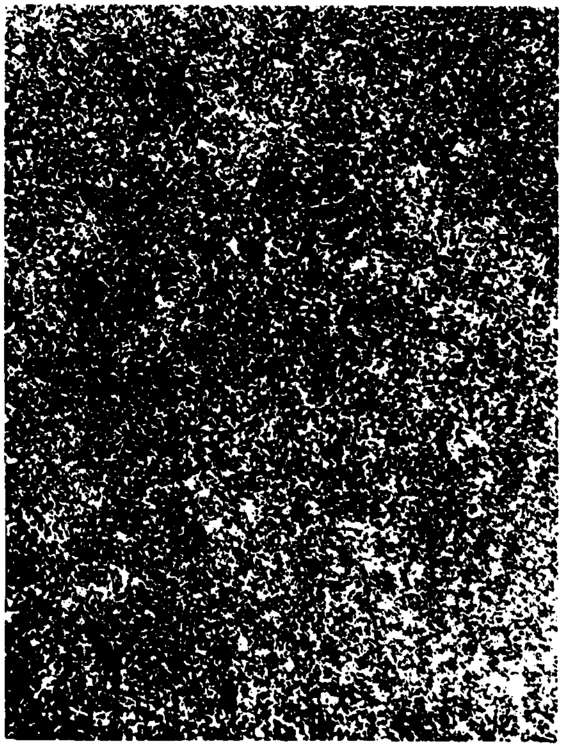


x500



x100

C



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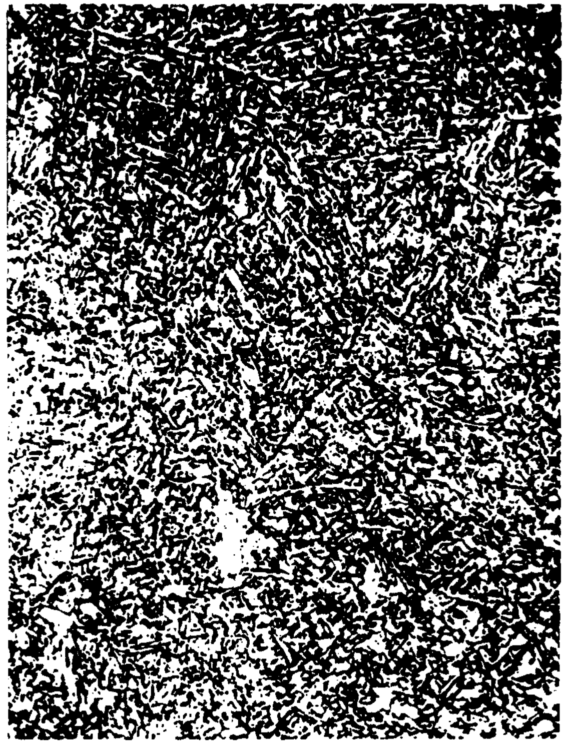

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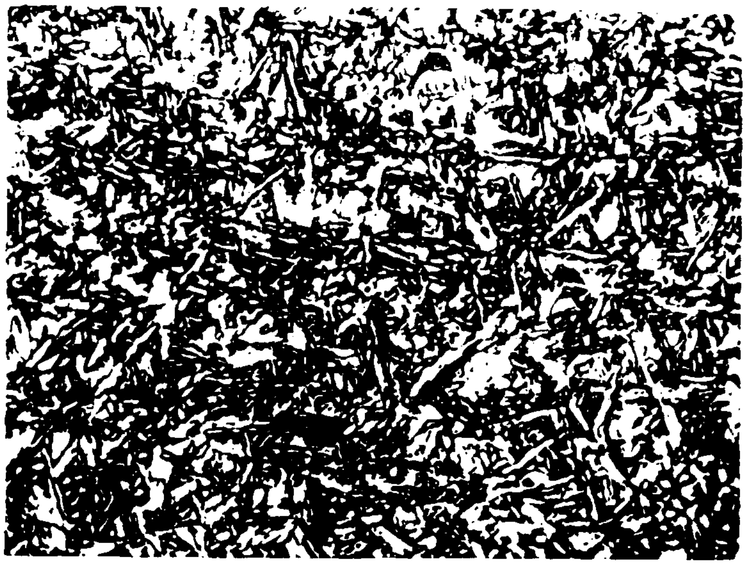

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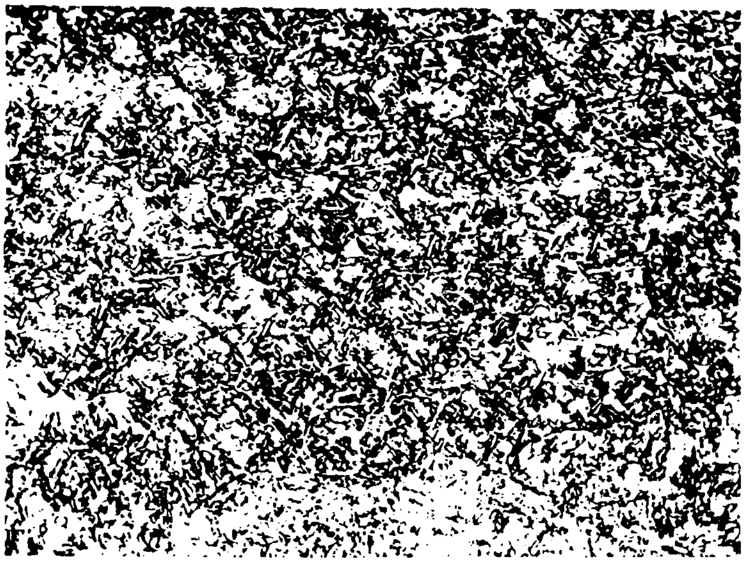


x250

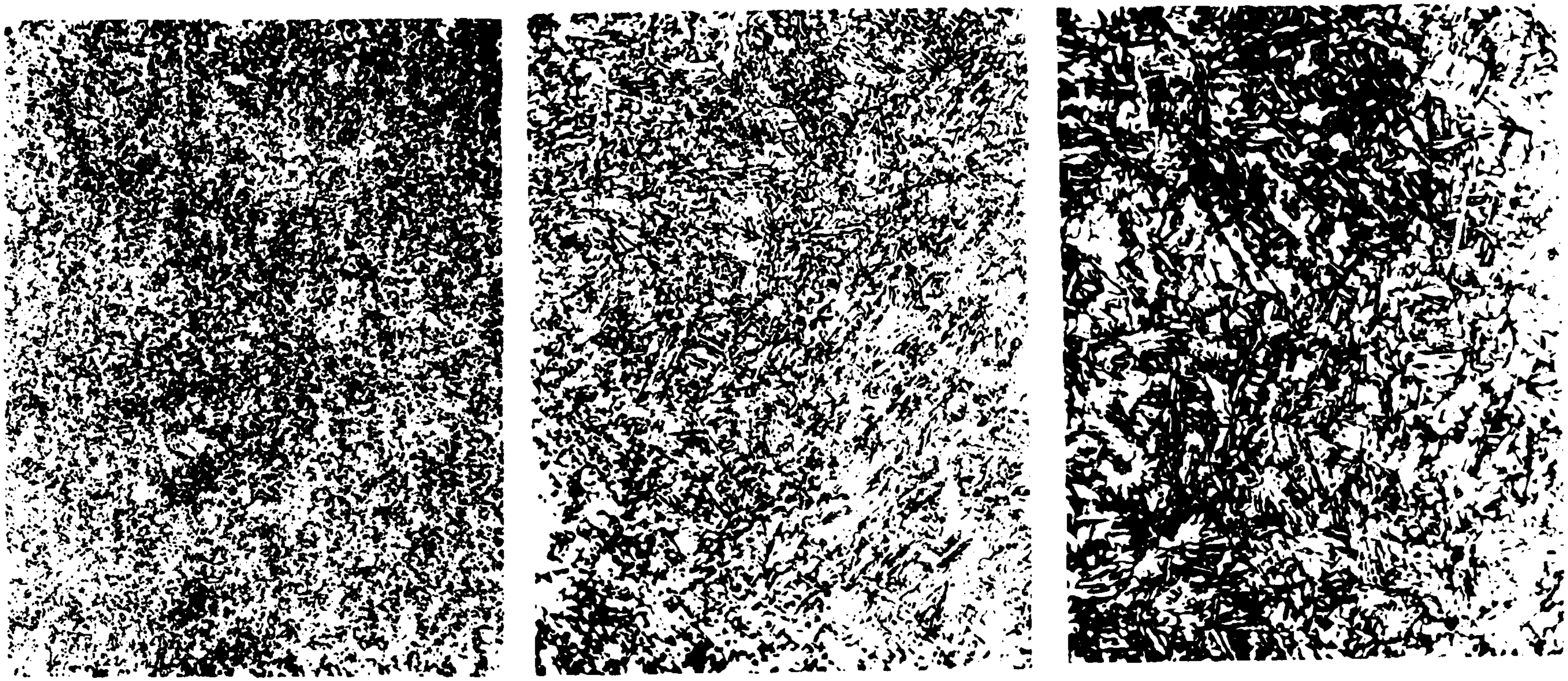
E


x75


x500


x1000

F



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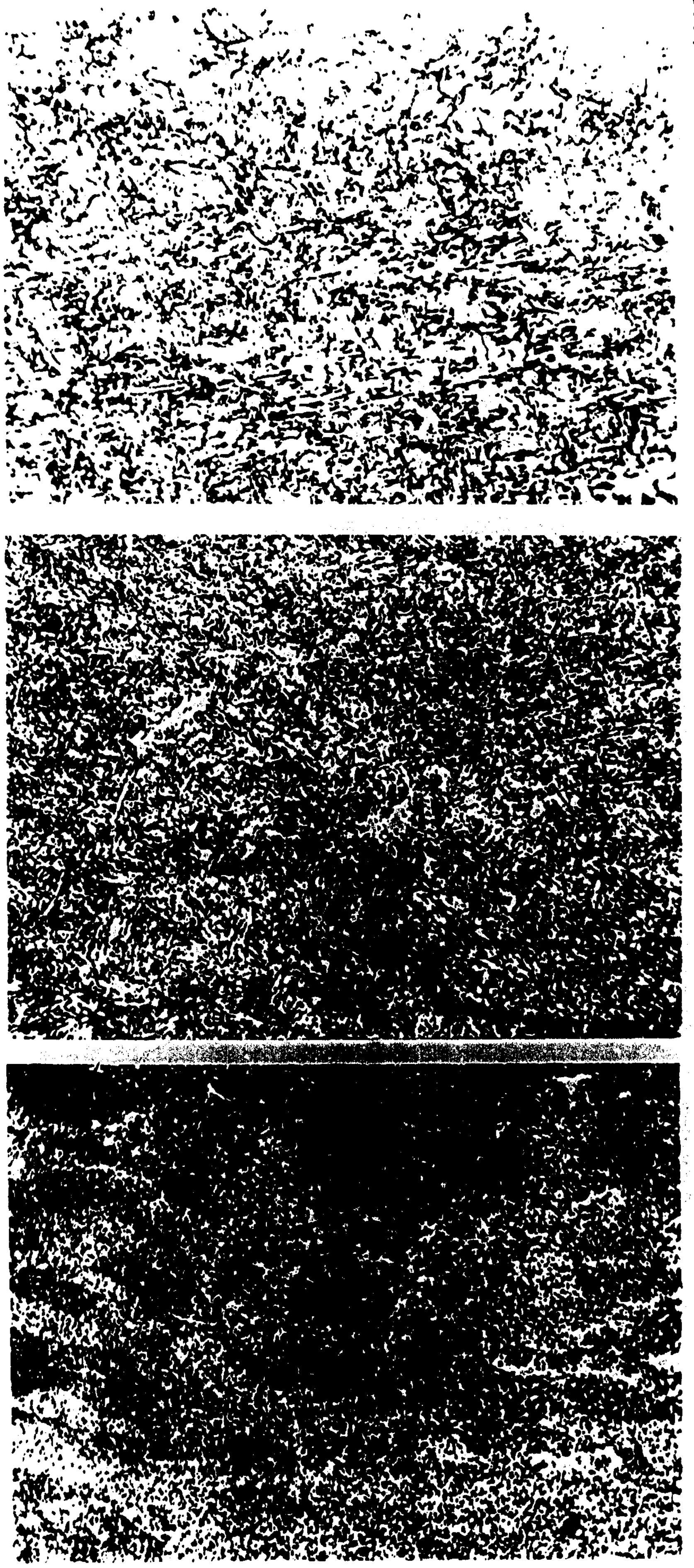

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x500

x75

H

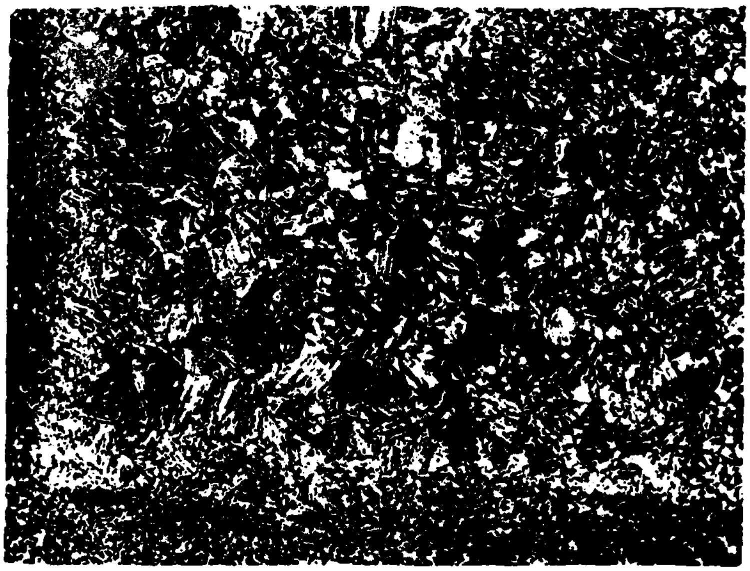
x75

x500

x1000

x1000

x500



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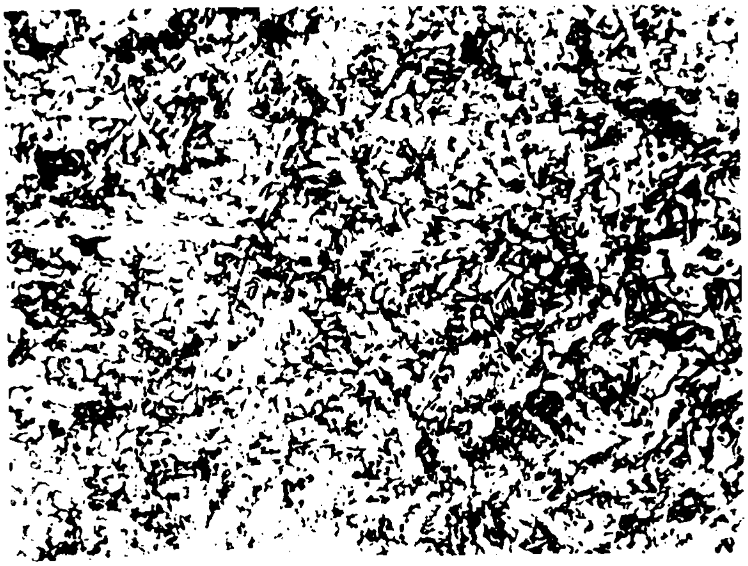

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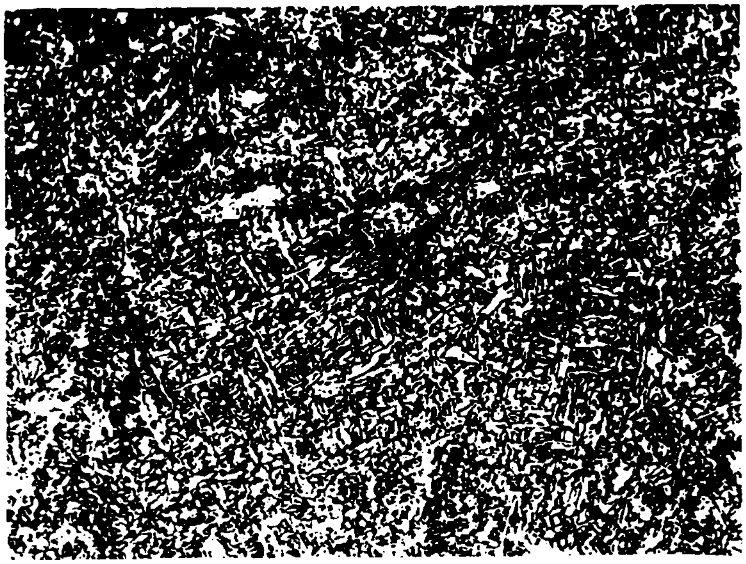

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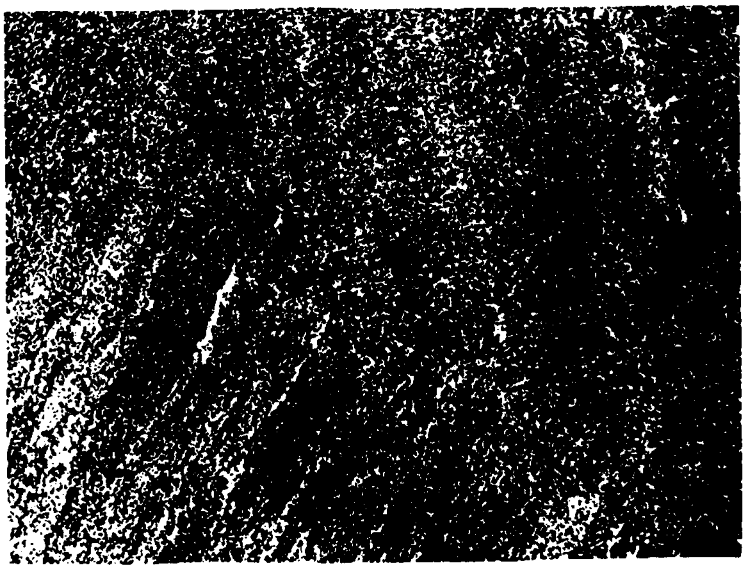


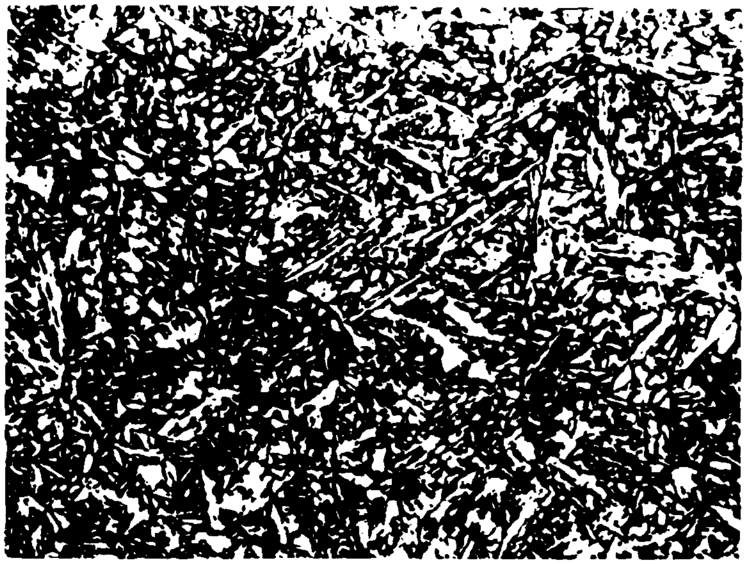
x75

K

x75

x250

x500



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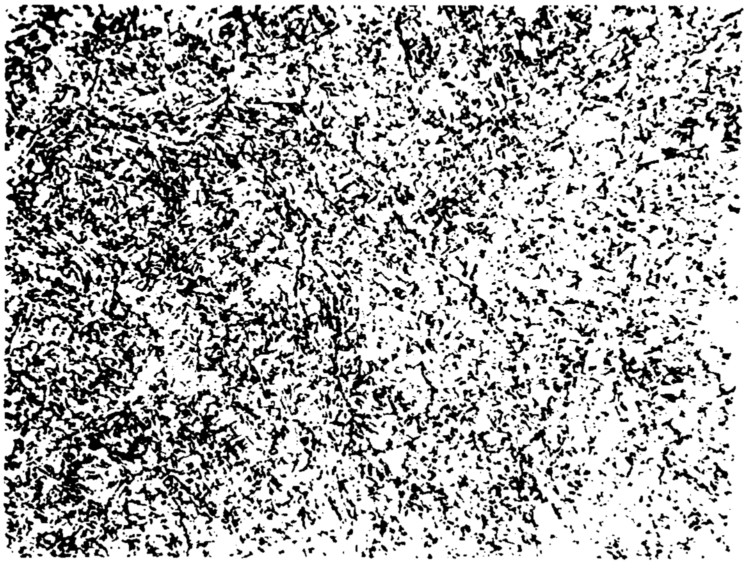

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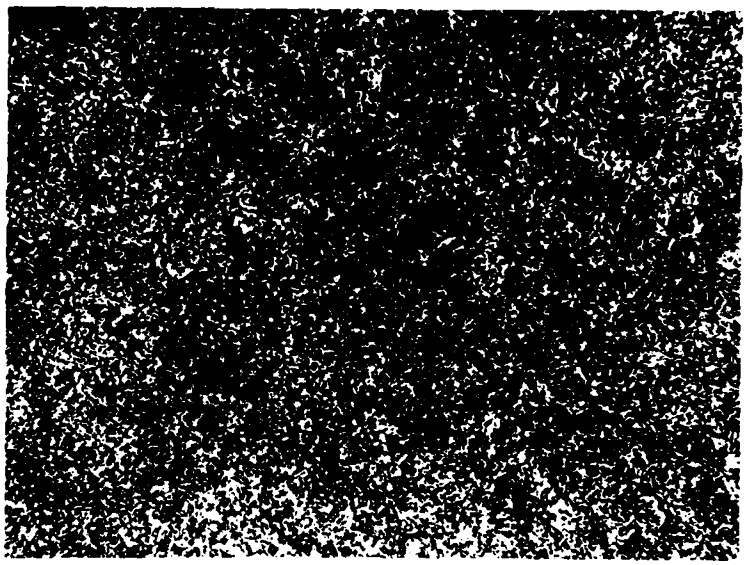


x75

M

x75

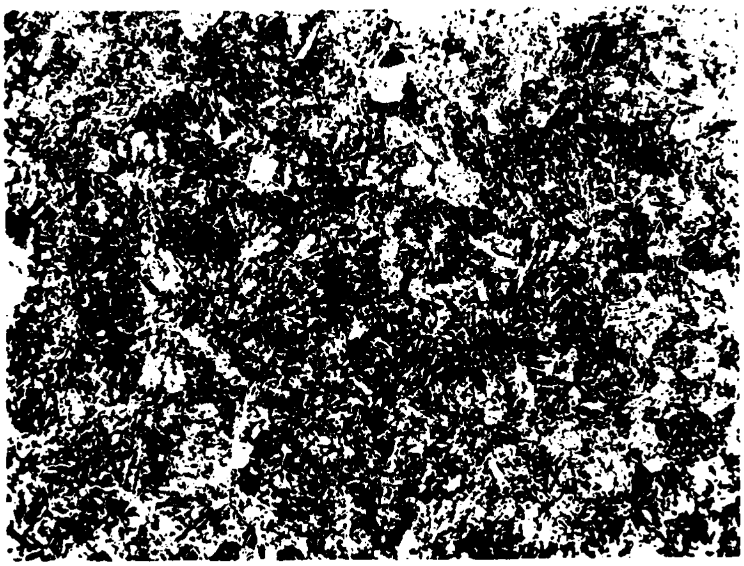
x100

x500

N


x1000


x500


x100

REPORT NO.	AR NO.	REPORT SECURITY CLASSIFICATION
MRL-TR-94-3	AR-008-624	Unclassified

TITLE

Evaluation of welding consumables and procedures for submarine construction

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REPORT DATE	TASK NO.	SPONSOR
February, 1994		

FILE NO.	REFERENCES	PAGES
G6/4/8-3656	13	37

CLASSIFICATION/LIMITATION REVIEW DATE	CLASSIFICATION/RELEASE AUTHORITY
	Chief, Ship Structures and Materials Division

SECONDARY DISTRIBUTION

Approved for public release

ANNOUNCEMENT

Announcement of this report is unlimited

KEYWORDS

Explosion Bulge Test
Weld Deposits
Welding
Heat Input
Weldment Zones

ABSTRACT

This report provides a summary of three developments in the welding of BIS 812 EMA and HY 590 high strength steels for the new RAN Collins Class submarine. Firstly, the established benchmark properties for Charpy energy, dynamic tear energy and elongation in the tensile test have been reviewed in the light of data collection from US, Australian and Swedish sources. A new set of benchmarks is proposed which takes into account the interrelationship between notch toughness, elongation and explosion bulge performance. Secondly, the influence of welding procedures (notably heat input) on weld toughness is discussed and heat input and preheat ranges are recommended which ensure that unrealistic welding parameters are not used simply in order to pass the explosion bulge test. Thirdly, a detailed microstructure and hardness survey on a weldment which marginally satisfied the requirements of explosion bulge testing is described. The results suggest that welding electrodes and procedures which were designed for the more traditional quenched and tempered steels such as HY 100 can also be used on the new BIS 812 EMA steels.

Evaluation of Welding Consumables and Procedures for Submarine Construction

Brian Dixon

(MRL-TR-94-3)

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